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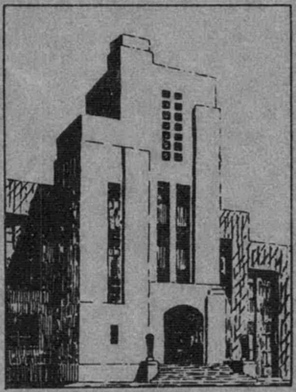
THE DAVID W. TAYLOR MODEL BASIN

UNITED STATES NAVY

THE 12-INCH VARIABLE PRESSURE WATER TUNNEL PROPELLER TESTING PROCEDURE

BY W. H. BOWERS



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NOVEMBER 1943

REPORT 505

NAVY DEPARTMENT
DAVID TAYLOR MODEL BASIN
WASHINGTON, D.C.

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PERSONNEL

Many members of the David Taylor Model Basin staff have had a hand in developing the procedure described here but those contributing most to the development of the past few years have been W.H. Bowers, L. Rubinowitz, and L.E. Wedding, all working under the general supervision of Commander A.G. Mumma, USN, formerly of the Taylor Model Basin staff.

Lieutenant J.T. Reed, USNR, a staff member now on military leave, rendered valuable assistance in the investigation of varying air content in the water.

A considerable amount of material in the report was taken from an earlier description of testing procedure by L. Rubinowitz. The completed report is the work of W.H. Bowers.

THE 12-INCH VARIABLE PRESSURE WATER TUNNEL
PROPELLER TESTING PROCEDURE

ABSTRACT

The procedure for testing model propellers in the 12-inch variable pressure water tunnel of the David Taylor Model Basin is described in detail, with special reference to the methods of measuring torque, thrust, and revolutions per minute for the propellers and water speed and pressure for the tunnel.

The testing procedure for a few representative propellers is followed through in detail, giving the formulas and coefficients used and tabulating all observed and derived data.

The method of making cavitation predictions for a ship is described and an example is given.

INTRODUCTION

The original installation of the 12-inch variable pressure water tunnel at the Washington Navy Yard was described in 1930 by Commander H.E. Saunders, (CC), USN, (1),* who set forth the purposes and objectives of the project. Although the arrangement and operation of the tunnel are still basically the same, many important improvements have been effected, both before and after its transfer to the David Taylor Model Basin in 1940. Lieutenant Commander A.G. Mumma, USN, has given a recent description (2) of both the 12-inch and the new 27-inch tunnels.**

Figure 1 is a general arrangement drawing of the 12-inch tunnel, taken from that paper.

Most variable pressure water tunnels are essentially similar within each of two general groups, distinguished by those which have open jets and those which have closed jets. The two TMB tunnels are of the open-jet type. The advantages of this type consist principally in easier access to and superior visibility of the models. However, the closed-jet tunnels are perhaps superior in regard to the uniformity of the water flow and the amount and stability of the air content. Lower test pressures can probably be obtained with the same or lower pump vacuums in closed-jet tunnels.

Anyone familiar with water tunnel work realizes that, as these are comparatively new items of model testing equipment, the testing technique can be expected to follow a lengthy and perhaps never-ending evolution, resulting

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* Numbers in parentheses indicate references on page 27 of this report.

** The latter has since been modified so that it now has a jet only 24 inches in diameter.

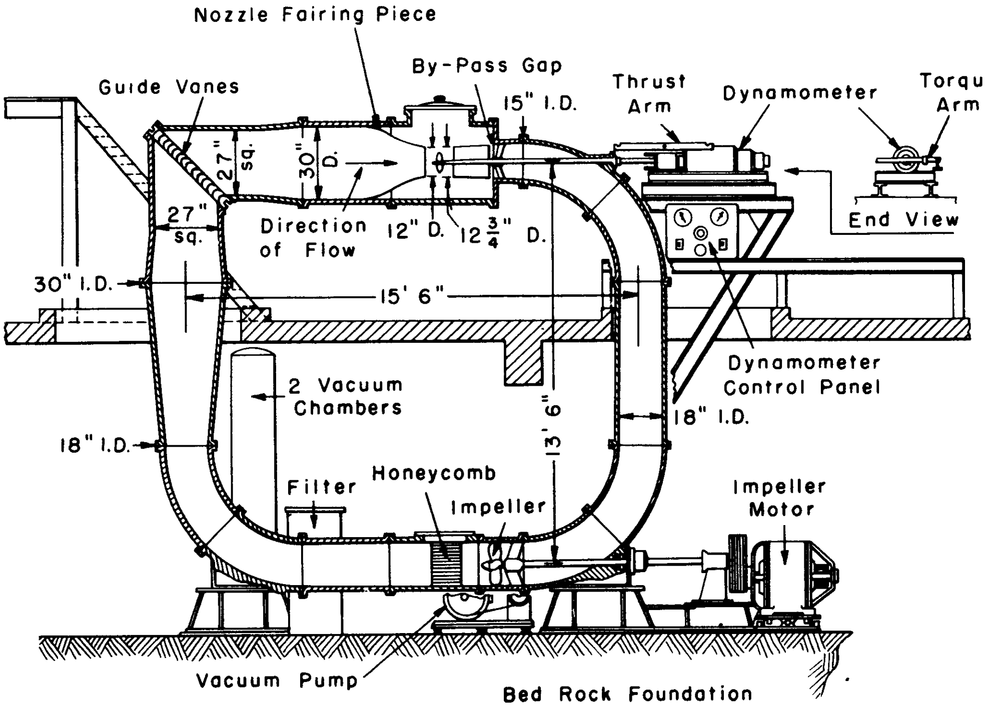

Figure 1 - 12-Inch Variable Pressure Water Tunnel - Schematic Section through Vertical Centerline Plane

from improvements in apparatus and from the acquisition of more knowledge. It is important that this progress be recorded from time to time, to benefit newcomers to the field and to allow widely separated investigators to compare their methods with mutual benefit. It is for these reasons that the present report has been written. From the preceding paragraph, it will have become apparent that some sections of this report will not apply to the operation of a tunnel with a closed jet.

DYNAMOMETER CONSTRUCTION

A dynamometer for propeller testing must provide for the accurate measurement of thrust, torque, and RPM. These objects may be accomplished by a number of different methods, but it has been found, at this tunnel, that the greatest accuracy and dependability have usually been attained through simplicity of construction.

Figure 3 of Reference (2) shows the appearance and general arrangement of the dynamometer and controls of the 12-inch tunnel. The motor is of 4-horsepower rating, with overload capacity to 6 horsepower, and has a maximum allowable RPM of 3000. Power for the motor is supplied by a direct-current variable voltage generator equipped with electronic voltage control. Armature and field rheostats on the control panel provide accurate speed

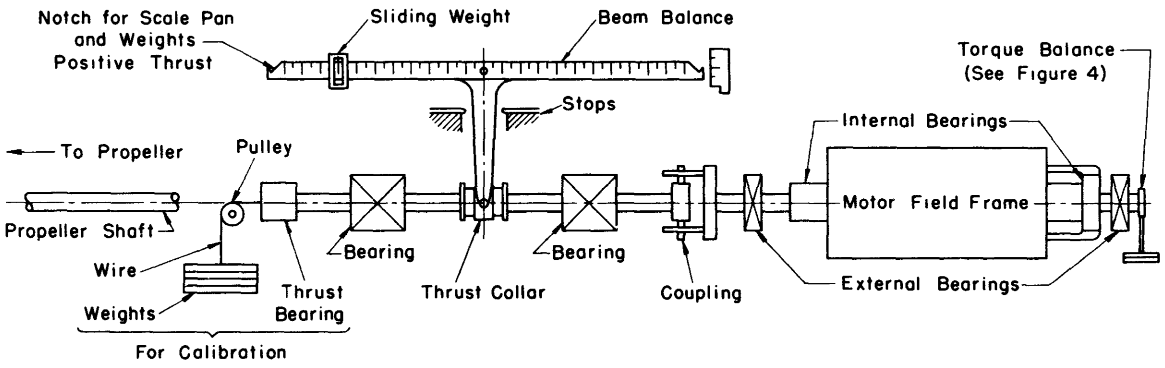

Figure 2 - Thrust Balance

This is a side view corresponding to that in the general arrangement in Figure 1. In normal operation the model propeller pulls itself toward the left and positive thrust is exerted in that direction.

control over the entire range. Figure 2 gives the schematic arrangement of the whole dynamometer as well as of the thrust balance. Details of each part of the dynamometer will be described when the use or function of the particular part is explained.

THRUST MEASUREMENTS

The arrangement for measuring thrust is shown schematically in Figure 2. The coupling indicated in the diagram to the left of the dynamometer motor transmits torque from the motor shaft to the model propeller shaft but leaves the latter free to deliver all its thrust to the balance. The thrust is transmitted from a ball-bearing thrust collar or housing on the propeller shaft through a fork to a short transverse arm at the near end of which is attached the beam balance. The levers, scales, and weights are proportioned to give readings of pounds and tenths of pounds directly. Customary practice is to set the weights at a selected thrust and to keep the beam balanced between its stops by minor variations in the motor speed. The arrangement of the balance permits the measurement of negative as well as positive thrust.

Each side of the balance scale reads up to 11 pounds. The removable weight pan, like each removable weight, is equivalent to 10 additional pounds. The total capacity is approximately 100 pounds of thrust in either direction.

THRUST CALIBRATION

Since the thrustmeter consists of only one rigid assembly in addition to the thrust bearing and since the pivots are mounted rigidly in ball bearings, there is little likelihood of the apparatus getting out of adjustment. To insure accuracy, it is necessary that the distance between pivots on the vertical lever arm be exactly correct. The readings of the thrustmeter are occasionally checked by disconnecting the dynamometer shaft and attaching a small thrust bearing and pulley provided for the purpose, as indicated in Figure 2. The length of the vertical lever arm is then adjusted to the proper value.

THRUST NO-LOADS

With atmospheric pressure in the water tunnel and a model propeller mounted on the shaft, a negative thrust is exerted on the shaft owing to the water flowing past the fairwater in front of the propeller hub. This is not present in the full-size ship propeller because the hub of the latter is almost invariably shielded by the shaft struts or bossings ahead of it.

This negative thrust depends upon two variables, the hub diameter and the water speed. A chart which may be used for determining this hub no-load thrust T_1 is shown in Figure 3. The data on this chart were obtained by using dummy hubs and fairwaters of the diameters indicated and driving the

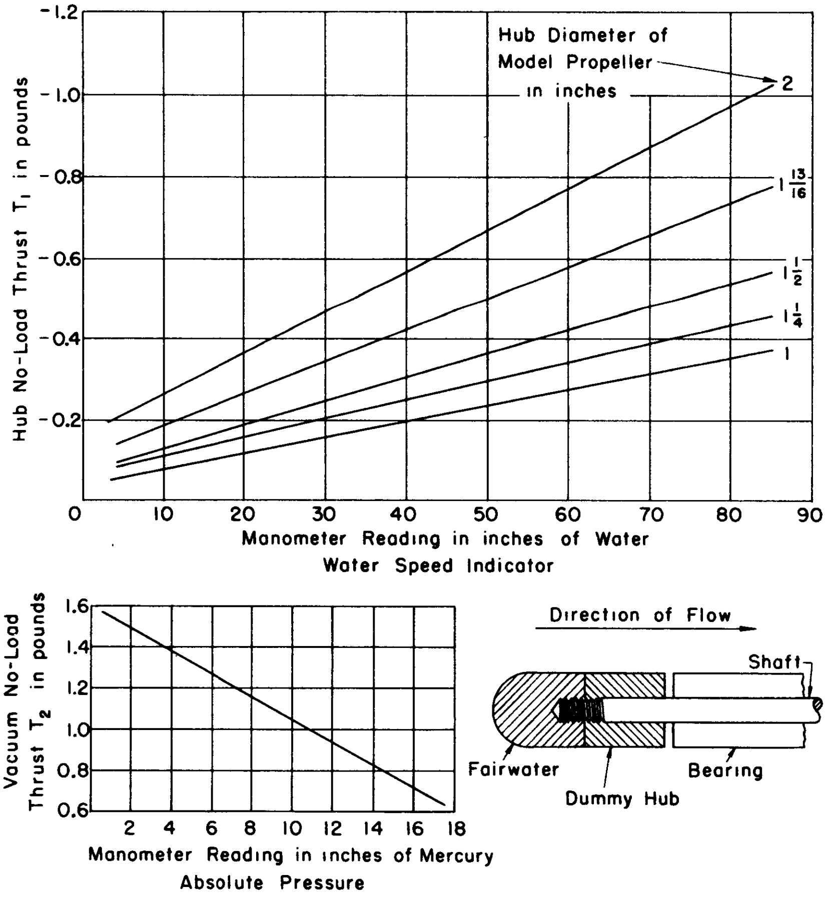

Figure 3 - No-Load Thrust Data for TMB 12-Inch Water Tunnel

water through the test chamber at various speeds. There may be slight deviations from these values for non-cylindrical hubs, but they are sufficiently accurate for most purposes. More accurate no-load thrusts may be obtained for any particular propeller at the time of the test by using the corresponding dummy hub.

T_1 is always negative, as it is opposite in direction to the propeller thrust on the ship. The absolute value of T_1 must therefore be added arithmetically to the thrustmeter reading to obtain the net propeller thrust.

With a vacuum on the water tunnel, there is an additional thrust to be considered because the propeller shaft acts as a piston, with reduced pressure inside the tunnel on the inner end and atmospheric pressure on the outer end. A curve of this vacuum no-load thrust T_2 is also shown on Figure 3, where T_2 is plotted against the readings of the mercury manometer which indicates the absolute pressure inside the tunnel. The correction for variations in atmospheric pressure which occur outside the tunnel is of second-order importance.

In the course of a test, when a given condition is set, T_1 and T_2 are picked off the chart and their algebraic sum is noted on the data sheet as the net no-load thrust. The latter is subtracted algebraically from the thrustmeter reading to obtain the net propeller thrust.

TORQUE MEASUREMENTS

The measurement of torque is accomplished by weighing the reaction torque of the stator of the motor which drives the model propeller shaft. As will be noted from Figure 2, there are external as well as internal ball bearings around the shaft at each end of the motor. The external bearings around the rotating shaft support the shaft, the armature, and the field frame, while the internal bearings support the field frame only. This remains stationary on the shaft except for a slight amount of rotation, between stops, on the internal bearings. The object of this arrangement is to insure live bearing support of the stator frame with consequent increase of sensitivity of measurement. The rotation of the stator is restrained by the weights on the balance arm which are used to measure the torque.

To avoid the use of electrical leads which, although flexible, might offer a slight restraint to the motion of the stator, current is conducted to the motor by a set of circular metal blade segments on the field frame dipping into fixed mercury wells.

The torque measured is the sum of the torque actually delivered to the model propeller and the no-load torque. The latter is composed of the frictional torque in the shaft bearings and the stuffing box, and the frictional drag on the propeller hub and fairwater.

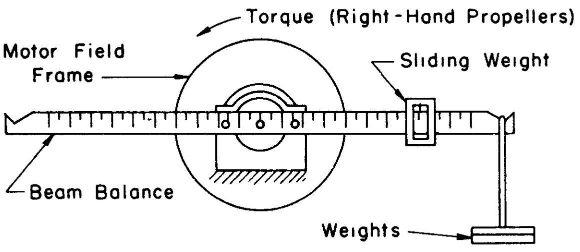

Figure 4 - Torque Balance

This is an end view of the dynamometer motor looking toward the tunnel. There is no damping on either the thrust or the torque balance.

As shown in Figure 4, the torque balance is rigidly attached to the rear end of the motor stator. Actually, the balance arm is carried by two projections from the stator which pass through clearance holes in the housing of the rear external bearing. The balance, being symmetrical, can be used to measure directly either right-hand (clockwise) or left-hand (counterclockwise) torque. Figure 4 shows the weights in proper position for the testing of right-hand propellers. Each division of the scale represents 0.05 pound-foot, and the scale reads up to 1 pound-foot on either side. Additional weights may be suspended at a distance of 1 foot from the shaft center.

During the taking of no-load readings, the dummy hub is rotated in the direction in which the model propeller is to turn. After a warming-up period of 15 or 20 minutes, readings of the torque balance are taken at intervals of about 200 RPM throughout the range of RPM of the test to be run. The actual no-load torque values for the various test conditions are then obtained by interpolation and subtracted from the total torque readings at corresponding RPM's of the test to give the net torque of the model propeller.

MEASUREMENT OF REVOLUTIONS PER MINUTE

The RPM readings are obtained from a dial geared to the shaft with a ratio of 100 to 1. The dial is rotated for a period of exactly one minute; a 60-second break-circuit chronometer controls a magnetic clutch which engages and disengages the shaft of the counter and the driving worm gear.

The lag in engagement and the lag in disengagement of the clutch are carefully equalized to prevent an error in the time interval. A contactor is provided on the RPM dial whereby the time for one revolution is occasionally accurately checked with a chronograph and any error detected. Alternately, whatever error is present may be determined by comparing the results of continuous runs of several minutes' duration with the averages of several regular runs. The effect of any error due to lag is largely eliminated in the longer runs.

WATER SPEED MEASUREMENT

In the early history of the 12-inch water tunnel, pitot tubes were used to calibrate the water speed manometer, with no model propeller in place.

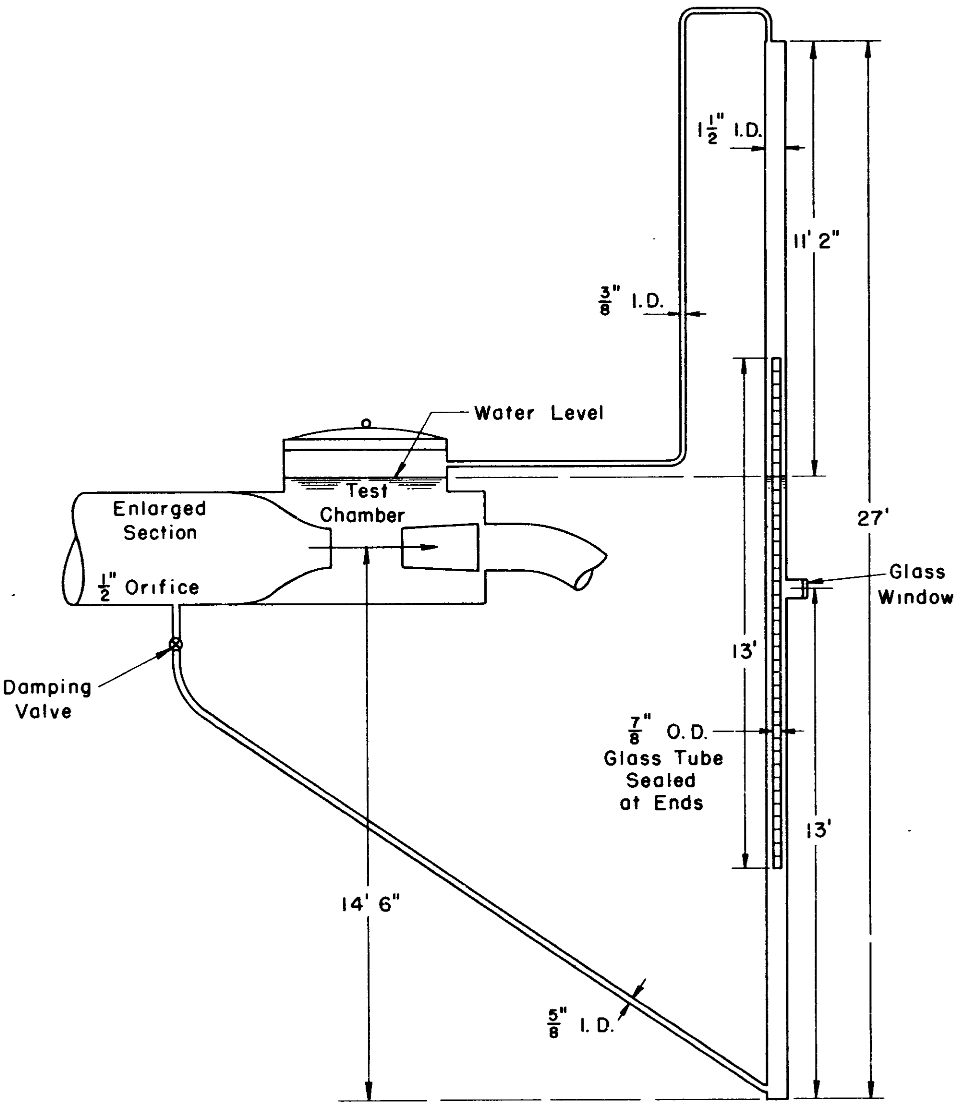

Figure 5 - Schematic Arrangement of Water Speed Manometer

The 5/8-inch water line which connects the enlarged section of the tunnel with the lower end of the standpipe must be led so that it vents itself automatically and remains entirely free of air.

But when model propellers were then put in for test the calibration was no longer accurate.

The water manometer measures the water speed by the static pressure developed in the enlarged section of the tunnel ahead of the nozzle. Although the details of the original installation no longer apply, the method of operation is the same. The schematic arrangement of the static pressure manometer is shown in Figure 5.* A 1/2-inch pressure tap is located in the

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* The novel type of speed manometer described here has been in use for nearly four years and has proved far superior to the ordinary type using mercury or some other liquid heavier than water.

wall of the enlarged section of the tunnel a foot or so ahead of the transition to the entrance or upstream nozzle. A pipe of 5/8-inch inside diameter with an adjustable valve for damping control connects the static pressure tap to the lower end of a high vertical standpipe. This connecting pipe must be run with the maximum possible slope at all points to avoid trapping air anywhere along it.

The lower half of the standpipe accommodates a long float in the form of a sealed glass tube which rises with the water level when the water in the tunnel is being circulated. The glass float is 13 feet long and carries inside it a scale graduated in inches. Through a port in the standpipe at the level of the operator's eye it is possible to read the scale in the float and thus to determine the reading corresponding to the water speed.

This manometer has several outstanding advantages:

1. Its zero reading serves as an excellent index for setting the water level in the test chamber.

2. The only part of it subject to breakage is the glass float and this is well protected within the standpipe.

3. The use of water as the measuring liquid makes for simplification and increases the sensitivity; this is over 13 times greater than for mercury.

4. It is necessary to read only one scale.

For determination of the exact water speed and calibration of the manometer a model propeller itself is ideally suited. The basic assumption for measuring speeds by this method is that there is one definite water speed at which a given propeller will develop a certain thrust when turning at a given RPM.

To determine the parameters affecting such a calibration, propellers of different sizes and types which had been carefully characterized in the model basin were tested in the water tunnel in the following manner. The thrust was first held constant at 0.0 pound and the water speed gradually increased in suitable increments so as to vary h, the net manometer reading, over its full range. For each reading of h, the RPM was measured and recorded. This procedure was then repeated twice, first with the thrust held constant at 30 pounds and then at 60 pounds.

From the thrust and RPM at each spot, C_T was computed from the relation $C_T = \dfrac{3600\,T}{N^2P^2D^2}$

where T is the thrust in pounds,

N is the RPM,

P is the pitch of the propeller in feet, and

D is the diameter in feet.

From the C_T curve of the basin open-water test, the slip ratio s was picked off for each C_T value as indicated in Figure 6. The water speed was then computed from the relation $V_A = \frac{NP(1 - s)}{101\frac{1}{3}}$

where V_A is the speed of advance in knots,
P is the pitch of the propeller in feet,
N is the RPM, and
s is the slip ratio.

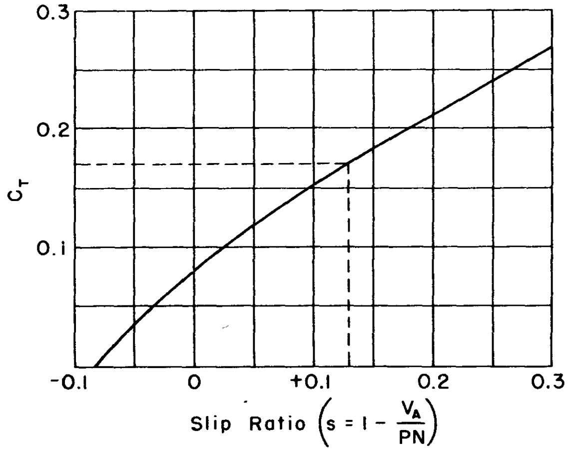

Figure 6 - Method of Obtaining Slip Ratio from C_T, Using an Open-Water Characterization Curve

A plot was then made of V_A in knots against h.

Examination of the test results of many propellers having variations of all the usual characteristics showed that the variations in diameter, pitch, mean width ratio, blade thickness fraction, and number of blades had no appreciable effect upon the relationship of V_A and h, but, as might be expected, thrust did have a slight but appreciable effect.

A plot was therefore made, using averaged and faired values of h and V_A from a large number of model propellers for thrusts of 0, 30, and 60 pounds. This procedure largely eliminates errors in individual determinations of these values. This plot is shown in Figure 7; it is kept convenient to the operator when a test is being run.

This calibration holds well for any propeller which is not too different from the conventional type. However, an individual calibration is usually made for any propeller which is characterized or used on a self-propelled model in the basin and for which cavitation data are desired. In the case of a simulated self-propelled test* the individual calibration insures that the RPM curve prior to cavitation agrees closely with the data obtained in the basin.

In a characterization test, it is probable that an average of the individual and general calibrations will lead to the most accurate water speeds. Any unusual differences between the individual and general calibration indicate that a basin retest is desirable for that individual propeller.

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* To be described subsequently.

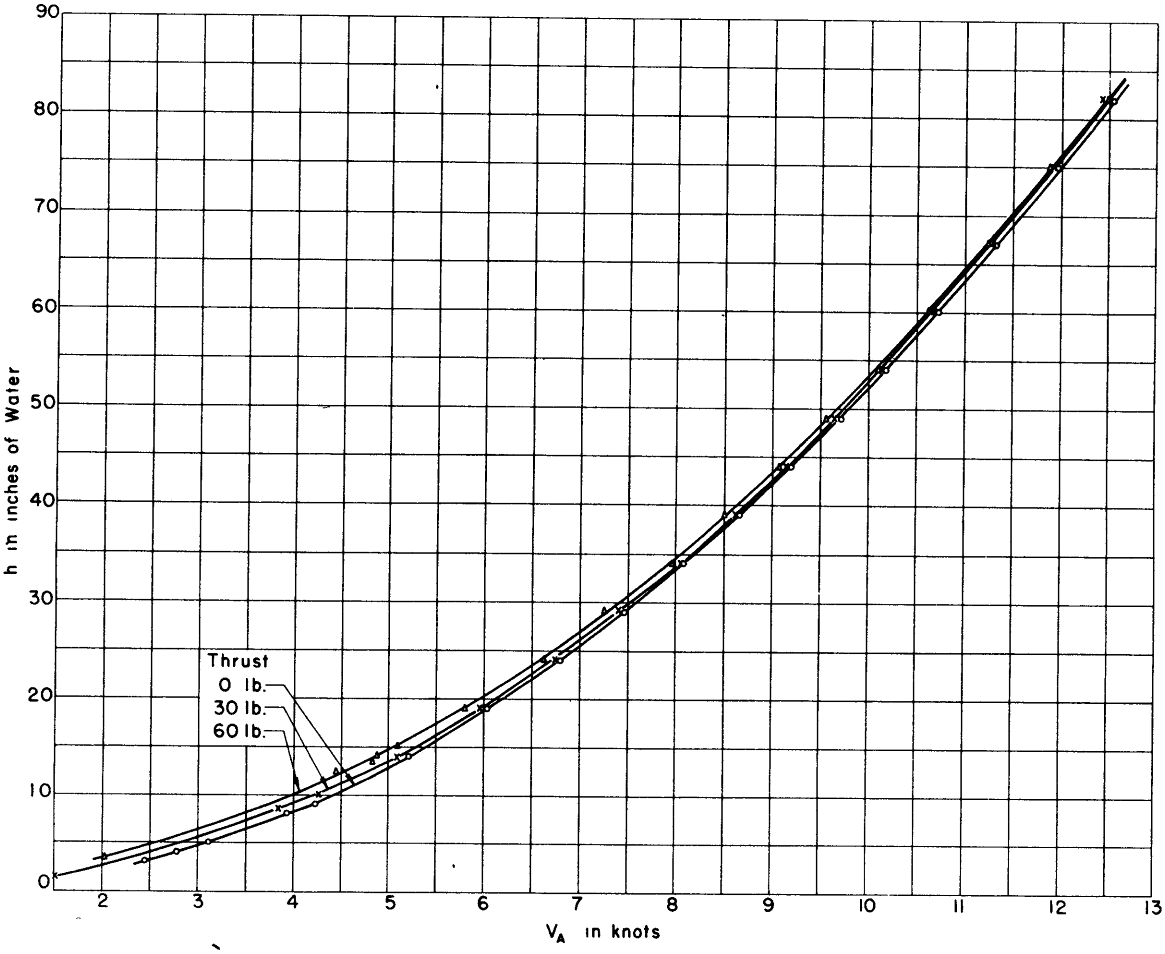

Figure 7 - Water Speed Calibration Curves for TMB 12-Inch Water Tunnel showing Variation with Thrust

PRESSURE MEASUREMENTS

The absolute pressure of the air above the free water surface in the test chamber of the tunnel is measured directly in inches of mercury by a U-tube absolute-pressure gage equipped with a cathetometer for accurate reading. A dessicator is provided in the line ahead of the manometer to prevent the entrance of moisture.

TEMPERATURE OBSERVATIONS AND CORRECTIONS

A thermometer is mounted inside the tunnel test chamber; it is placed near a port through which it can easily be read from the outside. When the water temperature is known, the water vapor pressure is readily found from the standard values in Table 1. As a test proceeds the temperature will gradually rise because of the heat generated by the impeller and propeller in moving the water. Formerly, cooling of the tunnel was provided by a refrigeration system, but it has been found entirely adequate to allow natural temperature fluctuations as long as the proper vapor pressure corrections are made.

TABLE 1

Vapor Pressure of Water from 50 degrees to 100 degrees Fahrenheit

These vapor pressures were converted from Table 75 on pages 165-166 of Smithsonian Meteorological Tables (1939).

Temperature degrees F.	Vapor Pressure* feet of water	Temperature degrees F.	Vapor Pressure feet of water	Temperature degrees F.	Vapor Pressure feet of water
50	0.411	67	0.756	84	1.333
51	0.426	68	0.782	85	1.376
52	0.442	69	0.810	86	1.419
53	0.459	70	0.838	87	1.466
54	0.476	71	0.867	88	1.514
55	0.494	72	0.897	89	1.562
56	0.512	73	0.928	90	1.611
57	0.531	74	0.960	91	1.663
58	0.550	75	0.992	92	1.717
59	0.570	76	1.026	93	1.770
60	0.591	77	1.061	94	1.826
61	0.613	78	1.096	95	1.883
62	0.635	79	1.133	96	1.941
63	0.658	80	1.170	97	2.001
64	0.681	81	1.209	98	2.063
65	0.705	82	1.249	99	2.127
66	0.730	83	1.290	100	2.192

* The vapor pressures are expressed in feet of water of specific gravity 1.00.

WATER LEVEL IN JET CHAMBER

The height of the free water surface above the centerline of the propeller shaft remains almost constant with changing conditions of flow and pressure; it is shown in Figure 8. There is a slight rise in level with increasing temperature owing to the expansion in volume of the water. This is taken care of by setting the level slightly low at the beginning of a test and permitting it to increase until it becomes slightly high. Experience and the rate of temperature change dictate the frequency of readjustment of the water level. Also there is a slight decrease with increasing water speed because some of the tunnel water goes into the water-speed manometer. This is corrected in the evaluation of the static water pressure, which is 1.36 feet with the water at rest. This is an arbitrary setting corresponding to a zero reading of the water-speed manometer of 3.8 inches. However, the water must stand almost this high to insure that all parts of the upper section of the tunnel are completely filled. The upper limit of water level in the test chamber is determined by the position of the vacuum line connection, which must remain somewhat above the water level.

AIR CONTENT OF THE WATER

A special problem which must be dealt with, if cavitation tests at reduced pressure are to be accurate, is that of the air and gas content of the water,* as the amount of gases in the water has been found to affect

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* Though it is known that other gases are included, they will all be classed as air in this report.

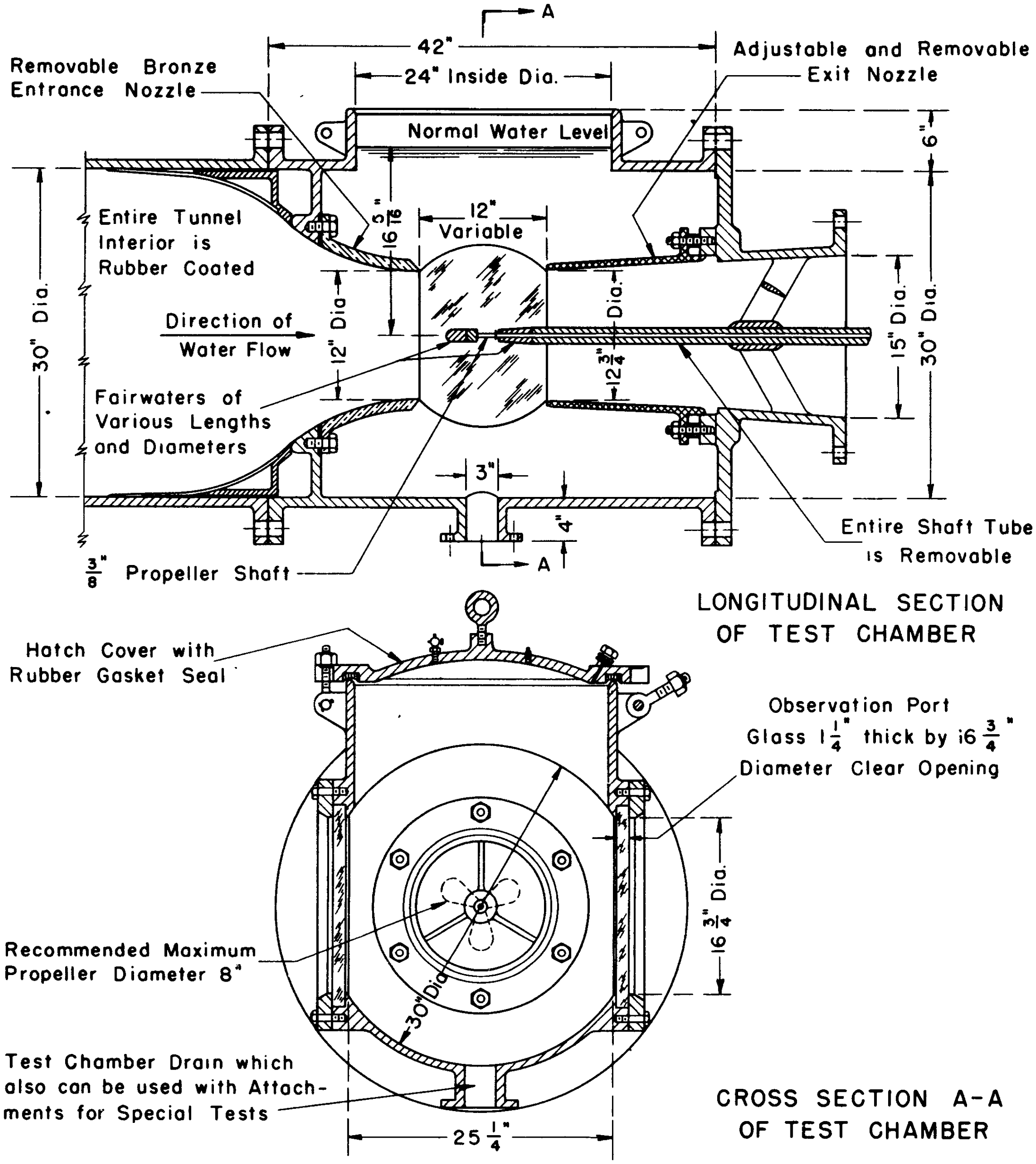

Figure 8 - Sections through Test Chamber of 12-Inch Water Tunnel

cavitation results to a marked extent. The tunnel water always contains an appreciable quantity of air, and new fresh water used in filling the tunnel is highly aerated. As a rule the air remains in solution until the water is subjected to a high vacuum. As the vacuum is maintained and the water is circulated the air content is gradually reduced. The rate of de-aeration is accelerated by faster circulation of the water and by keeping the vacuum as high as possible. The de-aeration process becomes slower as the air content decreases. Then if the vacuum is removed and the water again stirred, as in atmospheric pressure speed calibrations, air is re-absorbed. It is the present practice for cavitation tests to keep the air content at approximately the average condition resulting from intermittent running at a vacuum and at atmospheric pressure. The method of accomplishing this is as follows.

Two model propellers, 2066A and 1214 of the TMB list, are used as "standard" propellers to adjust the air content. It has been found that with "normal" air content Propeller 2066A at a water speed of 10 knots (h = 54.1 inches) and at a net pressure* of 2.54 feet of water, will develop a thrust of 37.60 pounds at approximately 1752 RPM. If Propeller 1214 is used at a water speed of 9.25 knots (h = 47.1 inches) and at a net pressure of 2.03 feet of water it will develop a thrust of 21.90 pounds at approximately 1842 RPM. Both propellers have well-developed cavitation under these conditions.

If the RPM's are too high, in developing these thrusts, the air content is higher than "normal" and if too low it is lower than "normal." To bring the conditions to normal the water is circulated either under a vacuum to draw air out of it, or under atmospheric pressure to put air into it. After the air content has been adjusted it is essential that some provision be made to keep it constant during a cavitation test. This is done by regulated leakage of air into the water to replace the air drawn out of it by the vacuum pump.

An air line runs from the dynamometer operator's station into a lower section of the tunnel a short distance ahead of the impeller. There are two valves in this line, a needle valve and a stop valve between the needle valve and the tunnel. The leakage can be started or stopped by operating the stop valve; the adjustment of the needle valve can thus be left undisturbed if desired. At the end of this line a rubber tube is connected to the metering device, which consists of a glass jar filled with water; the arrangement is shown in Figure 9.

When the valves are opened the pressure over the water in the jar is reduced and large air bubbles are periodically discharged from the mouth of the funnel. The frequency of formation and release of these bubbles indicates the rate of flow of air into the tunnel.

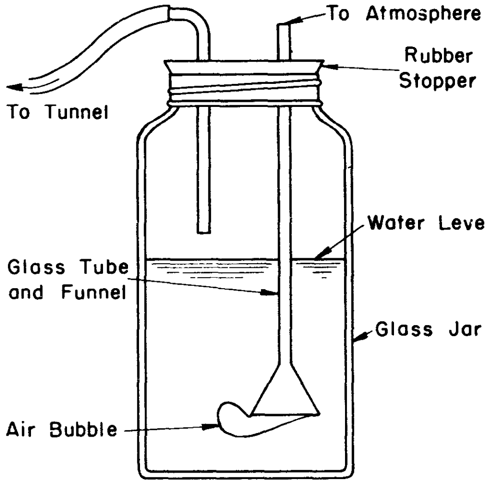

Figure 9 - Air Inflow Indicator

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* The net pressure is the sum of the air and water pressures above the centerline of the propeller shaft, less the vapor pressure of the water. See page 19.

The experience of previous tests, in which the air content remained constant or nearly so, aids in estimating the proper rate of flow as shown by the number of bubbles per minute, appropriate to the test conditions. Some general limits have been approximately determined. The metering device does not operate steadily at a rate above about 7 bubbles per minute and this provides only enough air for constant conditions at a net pressure of about 2.00 feet of water and a water speed of 10 knots. Also if the air leak is increased beyond this rate it becomes difficult to maintain pressures much lower than this. On the other hand it has been found that if the net pressure is in the neighborhood of 5 or 6 feet of water, little or no leakage is necessary to maintain equilibrium. Moreover the air-content factor seems much more stable then than at lower pressures, and whatever error there may be in air content is much less important at a high than at a low pressure. For these reasons it is imperative to use net test pressures as high as other limitations will permit.

After a test has been conducted according to the principles outlined here it is frequently the practice to substitute one of the reference propellers, 2066A or 1214, and to determine the validity of the test by establishing whether the air content has changed beyond an allowable limit. At present the allowable limit is taken as a variation in air content that will produce a 1 per cent error in the net pressures at which the reference propellers give the results quoted previously on page 13.

CHARACTERIZATION OF PROPELLERS

ATMOSPHERIC PRESSURE CHARACTERIZATIONS

Propellers may be characterized at atmospheric pressure in the water tunnel in a manner similar to the open-water tests in the model basin. As mentioned previously on page 9, the water speeds used in such a test are determined in a special individual calibration or from the general water tunnel calibration, or preferably from an average of the two.

Either of two test methods is used; in the first the propeller is run at constant RPM and the slip ratio is varied by changing the water speed; the thrust and torque are measured for each slip ratio desired. In the second, the water speed is held constant and the RPM varied. The choice of procedure depends largely upon the range of slip ratios to be covered; for a wide range of slip ratios it is better to vary the water speed, while for a relatively narrow range it is more convenient to use a constant water speed. In either case the basic principles and calculations are the same. Of course, the limitations of tunnel apparatus and of strength of propellers must always be taken into consideration in planning tests, but within these restrictions it is wise always to measure as large forces as possible.

After the data have been obtained, C_T, the thrust coefficient, C_Q, the torque coefficient, and e, the efficiency, are computed in the usual way.*

The values thus obtained from the test readings are plotted and curves are drawn.

To clarify the procedure the actual test of TMB Model Propeller 2189, run on 12 September 1941, will be followed step by step.

As a model basin characterization was available it was used as a basis for an individual speed calibration. It was decided to run the test at 10 knots water speed and at intervals of 0.05 in slip ratio from -0.05 to 0.30. For each spot the value of C_T was obtained from the basin open-water test and corresponding values of RPM and thrust were calculated from the relations $N = \frac{101 \frac{1}{3} V_A}{P(1 - s)}$ and $T = \frac{C_T N^2 P^2 D^2}{3600}$, respectively. The data thus obtained are listed in Table 2.

With the propeller in place and operating, the tunnel water speed was set to approximately 10 knots as determined from the general calibration, Figure 7 on page 10. Then the dynamometer rheostats were carefully controlled to maintain a net thrust of 1.10 pound, after application of the no-load correction. These initial conditions resulted in an RPM of 1339, as compared to the 1318 calculated from the basin test and shown in the first line of Table 2. The water speed was lowered and another run made. This time the RPM was exactly 1318, and therefore the torque was measured. The manometer reading was 55.0 inches, giving a net h of 51.2 inches, after subtracting the zero reading. This procedure was followed for each succeeding spot and resulted in the values of h and torque Q given in Table 3.

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* The formula for C_T is

$$C_T = \frac{3600\ T}{N^2 P^2 D^2}$$

where T is the thrust in pounds,
N is the revolutions per minute,
P is the pitch of the propeller in feet, and
D is the diameter in feet.

To obtain C_Q, the formula used is

$$C_Q = \frac{3600\ Q}{N^2 P^3 D^2}$$

where Q is the torque in pound-feet. Then the slip ratio is calculated from the relation

$$s = 1 - \frac{101 \frac{1}{3}\ V_A}{NP}$$

where V_A is the speed of advance in knots. The efficiency, e, is computed from the formula

$$e = \frac{C_T}{C_Q} \frac{(1 - s)}{2\pi}$$

TABLE 2

Thrusts Calculated from Basin Characterization Test

Slip Ratio	V_A knots	RPM	C_T*	T_m pounds
-0.05	10.0	1318	0.0135	1.10
0.00	10.0	1384	0.046	4.10
0.05	10.0	1457	0.0795	7.90
0.10	10.0	1538	0.1165	12.90
0.15	10.0	1628	0.157	19.45
0.20	10.0	1730	0.198	27.70
0.25	10.0	1845	0.238	37.90
0.30	10.0	1976	0.280	51.10

* Taken from the open-water characterization test in the basin.

TABLE 3

Results of Combined Tunnel Speed Calibration and Atmospheric Characterization

Slip Ratio	h inches	Q pound-feet	C_Q calculated	e calculated
-0.05	51.2	0.685	0.0115	0.196
0.00	52.2	1.09	0.0166	0.441
0.05	53.0	1.53	0.0210	0.572
0.10	53.0	2.075	0.0256	0.651
0.15	53.0	2.905	0.0320	0.663
0.20	52.7	3.77	0.0368	0.684
0.25	52.7	4.96	0.0425	0.668
0.30	52.7	6.40	0.0478	0.652

From these values of Q in Table 3 and RPM in Table 2, C_Q was calculated from the formula $C_Q = \frac{3600\,Q}{N^2 P^3 D^2}$. Finally, the efficiency e was calculated from the relation $e = \frac{C_T}{C_Q}\,\frac{(1 - s)}{2\pi}$ and C_T, C_Q and e were plotted on a basis of slip ratio. These are the atmospheric spots shown by the hollow circles on Figure 10; this figure also contains the results of the cavitation tests, to be described later.

CAVITATION CHARACTERIZATIONS

The cavitation characterization is now considered the basic type of test in the 12-inch water tunnel. This is an extension of the open-water characterization curves into the cavitation region by testing the propeller under several reduced pressures. From these curves complete knowledge may

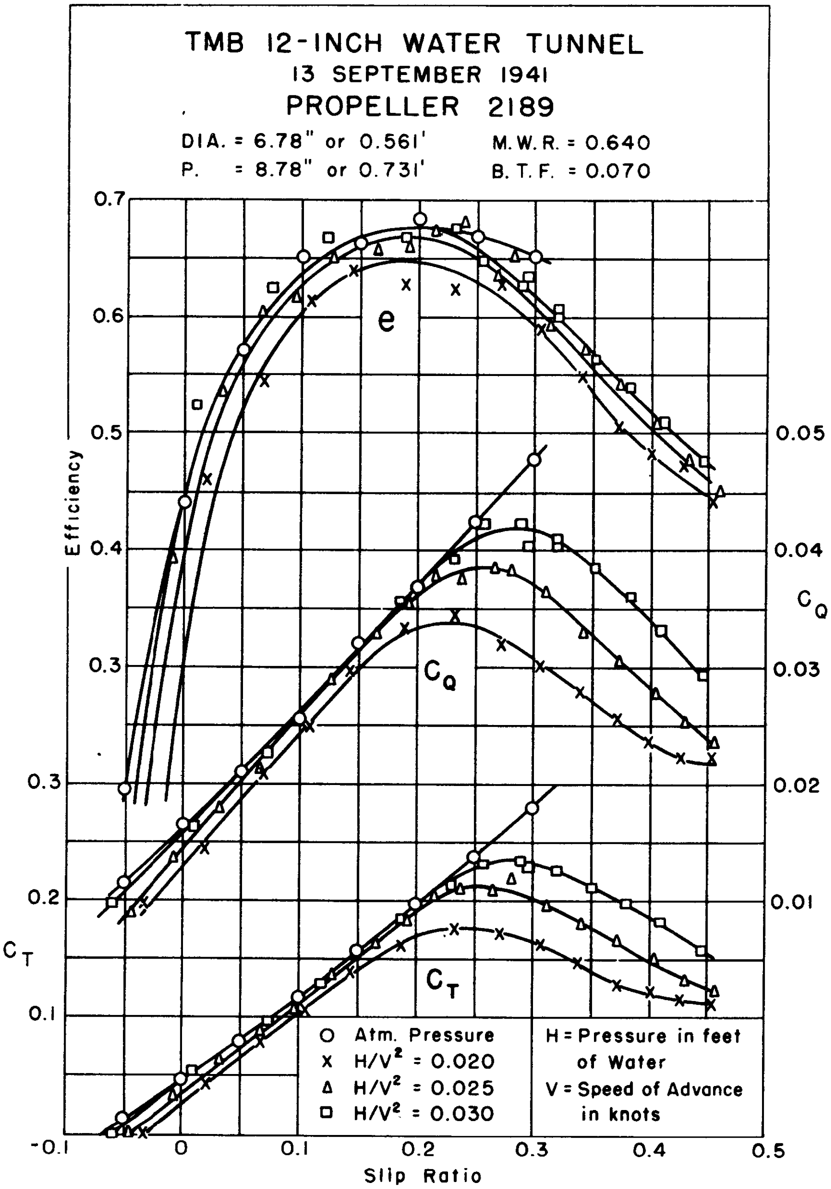

Figure 10 - Characteristic Curves for Propeller 2189

be obtained of the performance of a propeller under any set of conditions within the scope of the characterization. Thus, this constitutes a broad and complete record over large ranges of slip and it becomes unnecessary, generally speaking, to test the particular propeller subsequently. This is not true for the simulated self-propelled test, to be described later, as the latter gives results only for one special set of conditions.

The cavitation characterization of a model propeller may permit prediction of the performance of its prototype. The validity of these predictions has been verified by comparison of water tunnel, model basin, and ship trial results. Furthermore, valuable design data may be derived from the characterization.

The criterion of similitude in cavitation is the dimensionless ratio $\frac{P-e}{q}$

where P is the absolute static pressure, in feet of water,
e is the vapor pressure, in feet of water, and
q is the dynamic pressure, in feet of water.

This relation was tested experimentally and affirmed by Ackeret (3) in 1930. Others have also established that it is sufficient for similitude under cavitating conditions that this ratio be constant for all geometrically similar propellers, regardless of their absolute size. However, Gutsche has shown (4) in this connection that the Reynolds numbers may be of considerable importance, unless they be kept above the subcritical and transition zones, i.e., in the supercritical range.

$(P - e)$ may be held constant by setting the air pressure in the tunnel as desired by regulating the vacuum pump. The true value of q, for a given blade section, is dependent upon the square of the entrance speed along the axis of that section. However, the real entrance speed is never exactly known and instead of it the speed of advance is used. This remains, at the same slip ratio, in the same relation to the entrance speed for both ship and model propeller.

Thus it is sufficient for dynamical similarity to select the desired $\frac{P-e}{q}$ value and set the water speed and vacuum to hold this ratio constant throughout the test, provided the test speed is not too low, which would lead to running under the subcritical or transitional Reynolds numbers previously referred to. Lerbs (5) considers that a test speed of about 10 knots is sufficiently high for model propellers as used in most model basins and variable pressure water tunnels. While it is not certain that this speed assures Reynolds numbers in the supercritical range for all blade sections, it is thought that most of the scale effect is thus eliminated.

Instead of using the dimensionless ratio $\frac{(P-e)}{q}$, it has been found at the Taylor Model Basin more convenient for purposes of calculation to use the equivalent, though not dimensionless, ratio H/V^2

where H is the absolute static pressure at the shaft level minus the vapor pressure, both measured in feet of water, and
V is the water speed in knots.

To obtain a complete characterization, several values of H/V^2 are chosen which will produce cavitation throughout the range of slip ratios desired. Just what values will serve best can be judged from previous tests of similar propellers or by using a reliable criterion formula for the beginning of cavitation.

A formula developed by the writer and in use for several years at the TMB 12-inch tunnel is:

$$N^2 = \frac{37{,}500(1 - s)^{2s} H \frac{b}{f}}{PD}$$

where N is the revolutions per minute at which thrust is affected by cavitation,

s is the true slip ratio, defined as $1 - \frac{101 \frac{1}{3} V_A}{NP}$,

H is the net pressure in feet of water; it is the atmospheric pressure plus the submergence pressure to the centerline of the propeller, minus the vapor pressure,

b is the blade mean width ratio,*

f is the blade thickness fraction,*

P is the pitch in feet, and

D is the diameter in feet.

The tests of 12 and 13 September 1941 on TMB Model Propeller 2189 will again be followed to illustrate the method of making a cavitation characterization test. In this case it was decided that H/V^2 values of 0.020, 0.025, and 0.030 should be used, which at a constant water speed of 10 knots required net pressures of 2.00, 2.50, and 3.00 feet of water. As is customary, a run was first made at the middle value of H/V^2, so that if the results should be somewhat different than expected, the curve would still lie in the useful range and the other values of H/V^2 could then be modified to suit.

A description of the method of adjusting and maintaining the proper air content for cavitation tests has previously been given on pages 13 and 14. The net pressure of 2.50 feet of water was obtained in the following way.

2.50 feet + 1.135 feet (vapor pressure corresponding to a water temperature of 79.6 degrees F.) - 1.36 feet (head of water above shaft centerline) = 2.275 feet of water. Dividing this by 1.133 foot of water per inch of mercury gives 2.01 inches of mercury. Adding 0.01 inch for the manometer temperature correction gives 2.02 inches of mercury as the final pressure manometer reading.

After the pressure was set the water speed of 10 knots was obtained by adjusting the rheostats to give a net water speed manometer reading of 51.2 inches. This was the value determined in the atmospheric test described

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* Both as established by Taylor and as defined in Reference (6).

on page 15 for a thrust of 1.10 pound. The net thrust was adjusted to 0.0 pound and a run was made, during which the RPM and torque were measured. From this point the procedure was similar to that previously described for the atmospheric test, except that thrusts were arbitrarily picked at suitably spaced intervals, the water speed was adjusted accordingly and the RPM and torque were measured.

Practically all propellers reach an unstable zone in their performance as cavitation increases. When this happens, if the water is not extremely clean, small foreign particles will enhance cavitation and its effects. This has made it customary at the Taylor Model Basin to slow the propeller down before each run to remove any of these particles adhering to the leading edges.

The cavitation is noted at frequent intervals with a variable frequency stroboscopic light, which facilitates observation, and rough sketches of its extent and appearance are made. Single flash photographs are often made of a few conditions of cavitation, as shown in Figure 11.

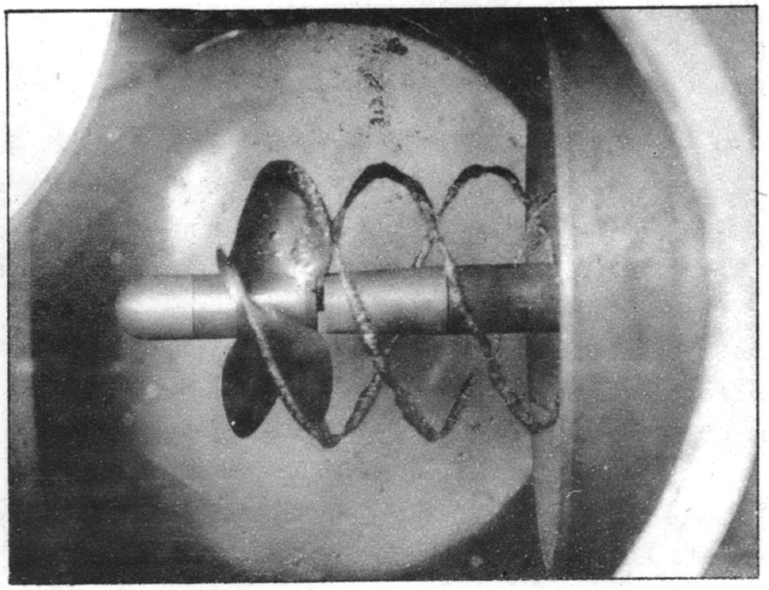

Figure 11 - Model Propeller Undergoing Test

This is a photograph taken by a single flash of 1/30,000 second duration produced by an Edgerton Kodatron Speed Lamp.

After completion of the test, in which successive values of the thrust were set and corresponding RPM's and torques were measured, the cavitation values of C_T, C_Q, and e were computed from the formulas given in the footnote on page 15. The calculations for the present test differ from those of the test at atmospheric pressure only in one minor respect: In the present case, C_T is computed from the arbitrary thrusts while in the preceding test the values of C_T had already been determined in the basin and the thrusts for the tunnel test were calculated from them. Because of the close similarity in the operations, values of C_T, C_Q, and e will not be tabulated here but are shown plotted against slip ratio in Figure 10, along with the results at atmospheric pressure.

SIMULATED SELF-PROPELLED TESTS

One of the most important functions of the variable pressure water tunnel is to complement the model basin self-propelled tests, to correct for the pressure discrepancy in the basin* and to regain similitude of pressure between model and full scale.

The basin tests make possible reliable estimates of ship propulsion performance provided cavitation on the ship propeller is not a factor. Ship propellers when cavitating turn at a higher RPM and absorb more power than is indicated by basin tests. It is then important to correct the basin tests by the results of tests at pressures defined by the law of similitude. Here again a dependable criterion formula indicates when cavitation is probable in full scale and when tunnel tests should be made. As implied in the preceding section on cavitation characterizations, the information required for correction of the basin curves may be obtained through calculation from the cavitation characterization curves. The given conditions are determined from the basin tests. Then for each point the proper value of H/V^2 is determined for entering the cavitation characterization curves. Then by the method of successive approximations the slip ratio is determined for which the RPM gives the required thrust. The corresponding torque is calculated from the C_Q value for the correct H/V^2 and slip ratio values. With the torque and RPM corrected for cavitation, the ship SHP is computed.

In many cases it is desirable to run only a simulated self-propelled test in the water tunnel as this test is much shorter than the cavitation characterization. Also general information may often be unnecessary, especially when the model propeller is likely to be used in only one test. When making this type of test the speeds ordinarily used are the speeds of advance obtained from the model basin test. This is a case where an individual atmospheric pressure speed calibration is made in the tunnel as described previously on page 9, using the RPM and thrusts of the model basin test.

After the speed calibration has been run the test proper is made with the same thrusts and water speeds under a reduced pressure. The pressure on the ship propeller, H_s, is calculated from information given with the basin test, and it is then corrected for 0.78 foot of water vapor pressure, which may be slightly higher than the average value for ship conditions, but is the figure which has long been used and upon which the testing technique has been based. H_s is then divided by λ, the linear ratio of ship to model, according to the law of similitude. The result is the theoretically

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* Conditions of similitude would require that the atmospheric pressure over the basin be reduced by the scale ratio, as well as the depth of water to the center of the propeller.

correct pressure for the model test, but experience has shown that the value of H_m thus obtained does not produce sufficient cavitation as compared to ship trial results. As a consequence a reduction of 15 per cent in this pressure has been found to give results more closely approximating ship curves and has been adopted. However, this procedure produces predicted SHP curves, allowing for cavitation, generally of somewhat greater slope than those of the ship, when plotted on a basis of speed. Methods of testing are being investigated for further refining the agreement between model and ship results with a view to the elimination of this constant factor.

It is frequently desirable to use higher values of RPM and speed of advance in the water tunnel when model basin tests have been made at low speed, so that the requirements of Reynolds' law are more nearly satisfied. A factor is chosen for arbitrarily increasing the water speeds within the speed and pressure limitations of the tunnel. The thrusts, RPM and pressure are then changed in accordance with the principles of dimensional analysis, i.e., the thrusts and pressure are multiplied by the square of the arbitrary factor. This insures that the H/V^2 and slip ratio values remain unaltered. Of course, the test data obtained must be properly reduced to give the correct RPM and SHP curves. This is accomplished as explained in an example which follows.

Still another method of running these tests is to keep the speed constant by using varying values of the multiplying factor mentioned in the preceding paragraph.

The water tunnel test of 15 February 1943 on TMB Model Propellers 2427 and 2428 will be followed in detailing the procedure for this type of test. These propellers had been used for self-propelled Test 8 on TMB Model 3757 in the model basin and the curves obtained there were to be corrected for cavitation.

With the model basin test data at hand, it was decided to start the water tunnel test at a speed corresponding to 30 knots and continue it at appropriate intervals up to 38 knots. To determine the necessary conditions for the test, data from the model basin test were tabulated in Table 4 and the calculations were made as follows:

$$V_m = \frac{V_s(1 - w)}{\sqrt{\lambda}}; \; T_m = \frac{33{,}000 \text{ EHP}}{101\frac{1}{3}\, V_s(1 - t)\, \lambda^3 \times 2 \times 1.024}; \; n = N_s\sqrt{\lambda}$$

where V_s is the ship speed in knots,

V_m is the model speed of advance in knots,

w is the wake fraction,

EHP is the effective horsepower for the ship,

TABLE 4

Model Water Speeds, Thrusts, and RPM's for Model Propellers 2427-2428 on Ship Model 3757, Linear Ratio λ = 20.5

V_s knots	$(1 - w)$	V_m knots	EHP	$(1 - t)$	T_m pounds	N_s	n
30	0.978	6.83	26,000	0.967	22.70	303.2	1303
32	0.981	7.31	31,850	0.967	26.10	325.2	1397
33	0.983	7.55	34,750	0.967	27.60	335.8	1442
34	0.984	7.79	37,650	0.967	29.05	345.5	1484
35	0.985	8.03	40,650	0.967	30.45	354.5	1522
36	0.984	8.25	43,700	0.967	31.80	363.8	1562
37	0.982	8.46	46,650	0.967	33.05	372.0	1598
38	0.980	8.67	49,650	0.967	34.25	380.5	1634

t is the thrust deduction,
T_m is the thrust of one model propeller,
N_s is the RPM of the ship propeller,
n is the RPM of the model propeller, and
λ is the linear ratio of ship to model.

The next step was to run the individual atmospheric pressure speed calibrations. This was done in a manner exactly similar to the calibration previously described on page 15 in connection with the atmospheric characterization. In this case it was unnecessary to measure torque but the water speed manometer readings had to be determined for the various speeds. This resulted in the values of h as shown in Table 5.

Following the speed calibrations, Propeller 1214 was placed in the tunnel and the air content was adjusted until the pressure necessary for the propeller to give its "standard" performance (page 13) was within 0.2 per cent of the correct value.

With Model Propeller 2427 in place, the air pressure was determined as follows:

	33.00	atmospheric pressure, feet of water
	+ 6.08	radius of propeller in feet
	+ 5.46	tip submergence of propeller in feet
Total	44.54	feet of water
	- 0.78	average vapor pressure for ship, feet of water
	43.76	feet of water, net pressure for full-scale propeller

Dividing 43.76 feet of water by the linear ratio, 18.45, and reducing the result by the regular 15 per cent, as described on page 21, gives 2.015 feet of water, which is the correct water tunnel test pressure. The temperature of the water was 79.9 degrees Fahrenheit, for which the vapor pressure is 0.823 foot of water. When this is added to 2.015 feet of water and the tunnel water head, 1.36 foot of water, is subtracted, the result is 1.478 foot of water. Then when this is converted to inches of mercury and the pressure manometer temperature correction is added, a value of 1.312 inch of mercury is obtained. The tunnel pressure was then set to obtain this manometer reading, which was maintained throughout the test.

TABLE 5

Water Speed Calibrations for Simulated Self-Propelled Test

V_s knots	V_m knots	h, inches of water	
		Propeller 2427	Propeller 2428
30	6.83	26.4	25.4
32	7.31	30.3	29.3
33	7.55	32.5	31.3
34	7.79	34.8	33.4
35	8.03	36.7	35.3
36	8.25	38.7	37.1
37	8.46	40.9	39.1
38	8.67	43.0	41.0

For the first spot corresponding to 30 knots, the water speed was set to give a net water speed manometer reading of 26.4 inches, the value determined in the calibration and shown in Table 5. The thrust was held to 22.70 pounds as calculated in Table 4 and the torque and RPM were measured. The run was repeated, as is the custom, and the average value of the net torque was found to be 2.88 pound-feet and for the RPM the average was 1304. The other spots were run in the same way and Propeller 1214 was again used to check the air content. This time it was found that the pressure required for it to give its "standard" performance was in error by 0.7 per cent. As this was within the allowable deviation, explained on page 14, the left-hand propeller, Model 2428 was then tested similarly.

TABLE 6

Torques and RPM's obtained in Simulated Self-Propelled Test

V_s knots	Net Thrust pounds	Propeller 2427		Propeller 2428	
		Net Torque pound-feet	RPM	Net Torque pound-feet	RPM
30	22.70	2.88	1304	2.81	1302
32	26.10	3.29	1398	3.28	1400
33	27.60	3.56	1444	3.50	1447
34	29.05	3.80	1495	3.74	1499
35	30.45	3.97	1545	3.93	1544
36	31.80	4.23	1630	4.13	1615
37	33.05	4.45	1706	4.35	1680
38	34.25	4.64	1802	4.51	1780

TABLE 7

Derived Full-Scale RPM and SHP

V_s knots	Propeller 2427		Propeller 2428	
	RPM	SHP	RPM	SHP
30	303.5	39,480	303.0	38,500
32	325.5	48,380	326.0	48,300
33	336.0	54,050	337.0	53,300
34	348.0	59,750	349.0	58,950
35	359.8	64,500	359.5	63,800
36	379.5	72,500	376.0	70,100
37	397.2	80,200	391.0	76,850
38	419.5	87,950	414.5	84,400

The data obtained in these tests are listed in Table 6. These data were then reduced to ship SHP and RPM by using the relations:

$$N_s = \frac{n}{\sqrt{\lambda}}, \qquad \text{SHP} = \frac{2\pi n Q\, \lambda^{\frac{7}{2}} \times 2 \times 1.024}{33,000}$$

The results are set down in Table 7.

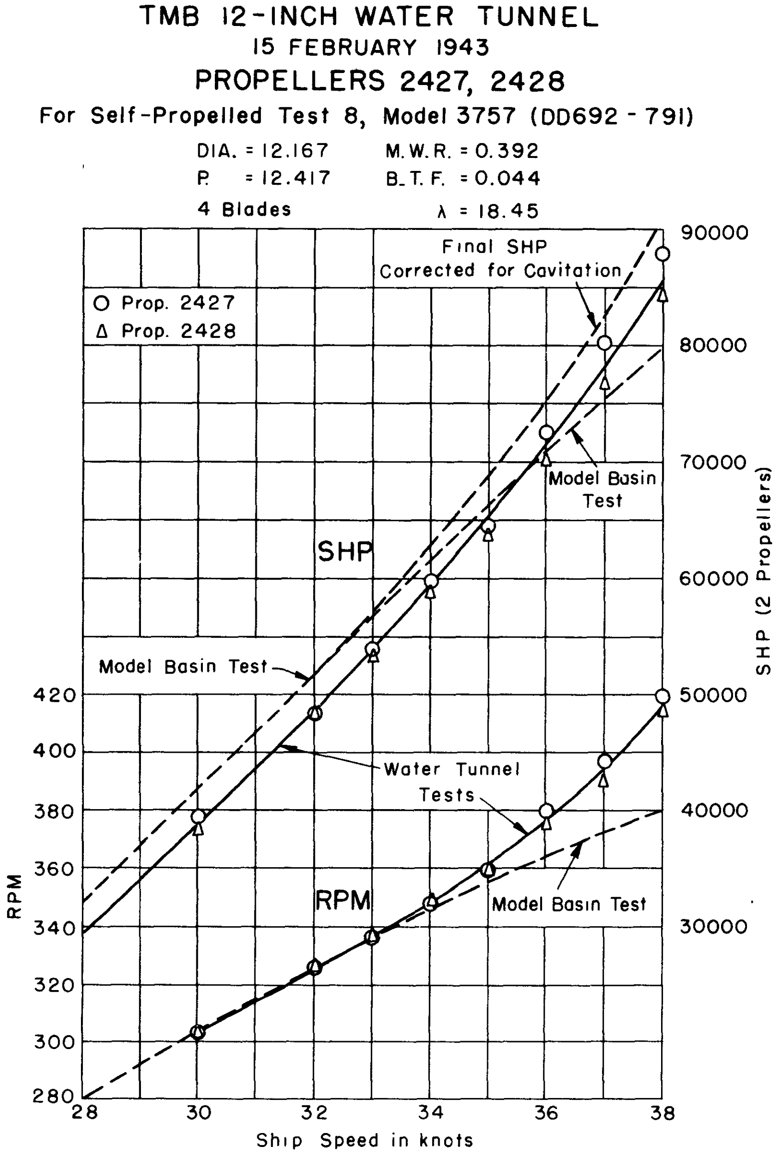

Figure 12 - Predicted SHP and RPM Curves from Tests of Propellers 2427 and 2428

These values of N and SHP were plotted on a base of ship speed as shown in Figure 12. On the same sheet the RPM and SHP curves from the model basin self-propelled test were copied to the same scale. As will be seen, the RPM curve of the water tunnel test coincides with that of the model basin up to a ship speed of about 32 knots. From this point the water tunnel curve shows increasing divergence from the model basin curve due to the effects of cavitation. In the case of the SHP curve, it will be noticed that the water tunnel curve is somewhat lower than the model basin curve. This is generally true and should usually be expected because the efficiency of the propeller in free water, as in the tunnel test, is usually higher than its efficiency when propelling the ship model, due to shaft angularity, minor hull effects not compensated by wake and thrust deduction coefficients and absence of the strut, shaft, and hull in the water tunnel tests. Like the RPM curve the water tunnel SHP curve begins to rise, in relation to the model basin curve, at about 32 knots ship speed.

In accordance with usual practice the water tunnel SHP curve was then shifted upward at every point by the amount of shaft horsepower necessary to bring it into agreement with the basin curve at 32 knots. From this speed on, the water tunnel curve, after being shifted, fell above the basin curve and the difference was taken to represent the effect of cavitation on the ship.

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